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Mass Measurement Techniques for High-Speed Flyby Reconnaissance Missions of Potentially Hazardous Asteroids

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Objective:

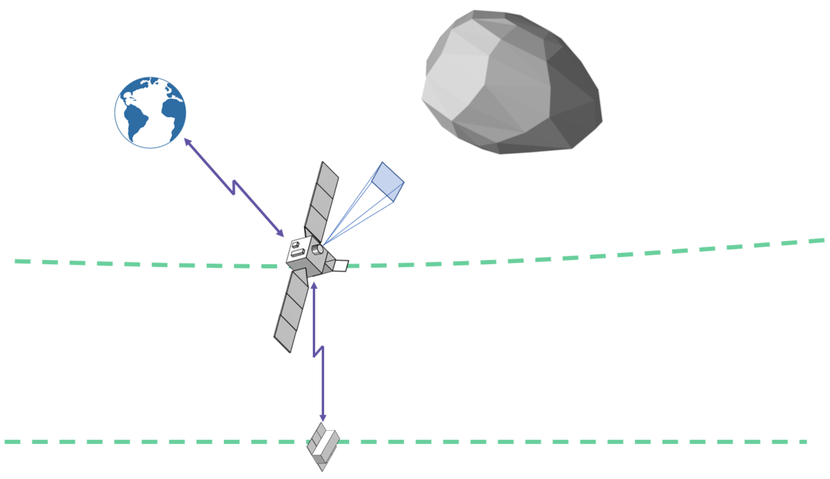
Our objective is to evaluate the effectiveness of mass estimation using intersatellite ranging and Doppler for high-speed asteroid flybys, using simulation of relevant planetary defense scenarios.

Roughly 12 days prior to the flyby, a host spacecraft dispenses a CubeSat test-mass. The pair of spacecraft then execute a series of maneuvers to target a simultaneous flyby. The host targets a very close approach of 2 body diameters (spherical equivalent). The CubeSat targets a more distant 10 km separation.

The host conducts coherent radio navigation with the DSN, optical navigation to the asteroid, optical images of the test-mass, and coherent radio navigation with the test-mass.

Parameter	Value
Host Mass	500.0 kg
Host SRP Area	5.5 m^2
Host SRP Nominal Cr	1.0
Host SRP Cr *a-priori* 1σ	1.667%
TM Separation	10 cm/s
TM Separation 1σ per axis	5 cm/s
TM Mass	12.0 kg
TM SRP Area	0.2 m^2
TM SRP Nominal Cr	1.0
TM SRP Cr *a-priori* 1σ	6.667%

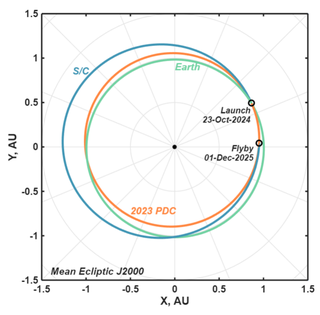
Measurement	1σ
DSN Doppler Noise	0.1 mm/s
DSN Range Noise	0.5 m
DSN Range Per-Pass Bias	1.5 m
Optical Meas (RA, Dec) Noise	1 urad
Intersatellite Doppler Noise	0.1 mm/s
Intersatellite Range Noise	10.0 m
Intersatellite Range Bias	1.5 m

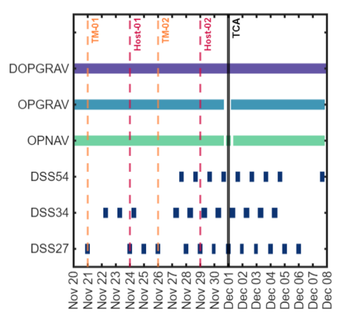


Case 1: Slow Flyby of 2023 PDC

Flyby Speed: 1.7 km/s
Size: 800 m
Host Maneuvers: 2
Test-Mass Maneuvers: 2

2023 PDC is the target in the 2023 Planetary Defense Conference Hypothetical Threat Exercise. It was discovered 13 years prior to a potential impact.

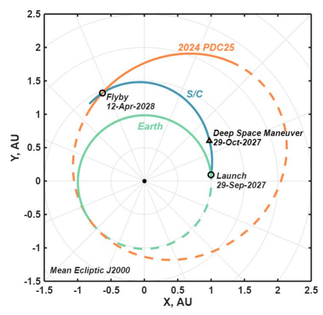


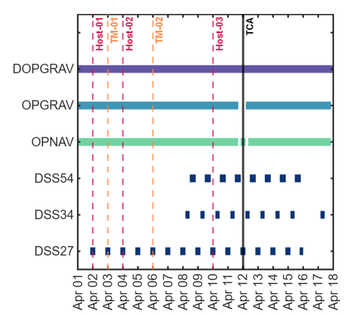


Case 2: Medium Flyby of 2024 PDC25

Flyby Speed: 8.1 km/s
Size: 150 m
Host Maneuvers: 3
Test-Mass Maneuvers: 2

2024 PDC25 is the target of the 2025 Planetary Defense Conference Hypothetical Threat Exercise. It was discovered 17 years prior to a potential impact.

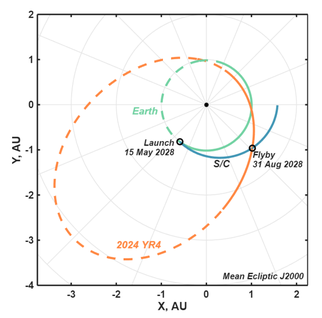


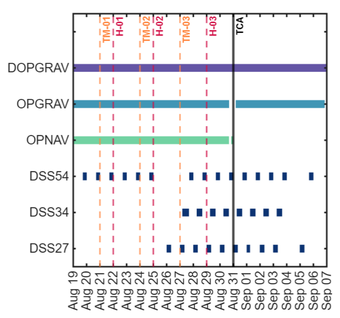


Case 3: Fast Flyby of 2024 YR4

Flyby Speed: 22.0 km/s
Size: 60 ± 7 m
Host Maneuvers: 3
Test-Mass Maneuvers: 3

2024 YR4 was discovered in December 2024 and briefly achieved a 3.1% probability of impacting Earth in 2032. We designed a rapid response flyby trajectory prior to the probability of collision becoming negligible.





Results:

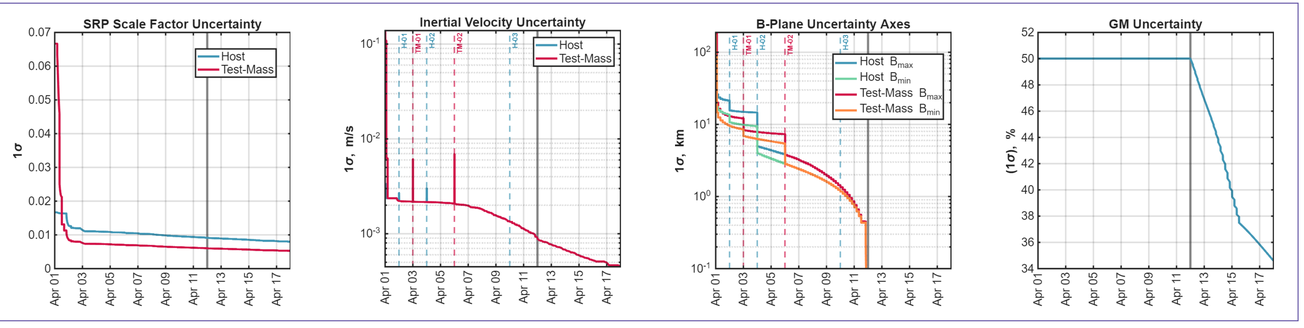
The baseline simulation parameters indicate the following:

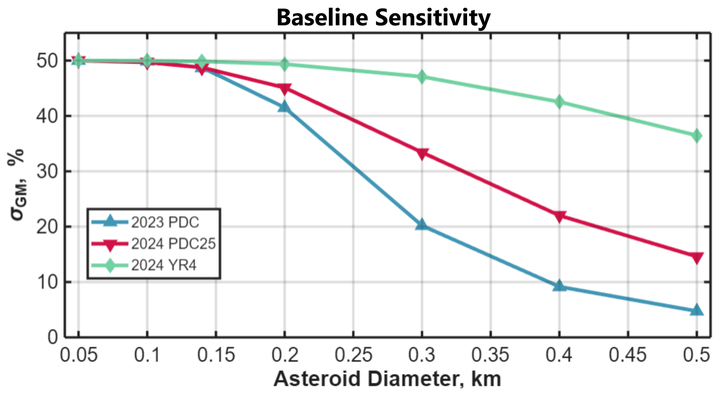
- The 2023 PDC case provides a measurement of <5% (1σ).
- The 2024 PDC25 case provides only a marginal improvement in the mass estimate. Perhaps this would be useful for confirming a non-metallic composition.
- The 2024 YR4 case is not observable.
- Aside from asteroid size and flyby speed, the asteroid's mass (GM) observability is most sensitive to the two spacecrafts' solar radiation pressure (SRP) uncertainties.
- The fastest flyby will require a modified maneuver schedule to meet the required B-Plane targets.

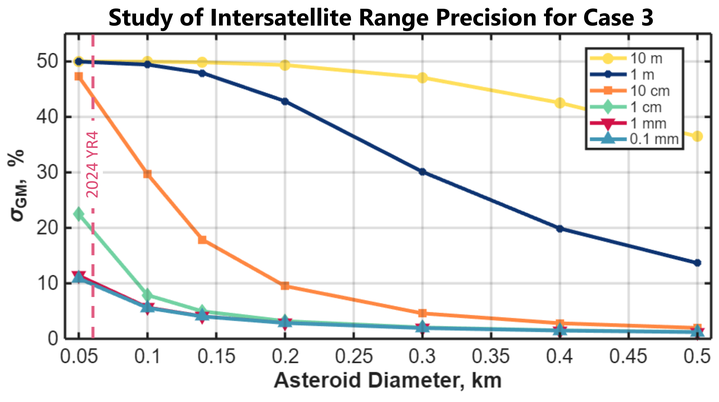
To better understand a potential improvement, we parameterized the intersatellite range precision for the 2024 YR4 (60 m, 22.0 km/s) case and found:

- If we can achieve a range precision of 10 cm (2 orders of magnitude improvement), the mass could be measured to ~40% (1σ).
- If we can achieve a range precision of 1 cm (3 orders of magnitude improvement), the mass could be measured to ~20% (1σ). This case would be broadly applicable to most planetary defense rapid reconnaissance flyby scenarios.
  - However, we caution that the very low flyby distances will require further study to determine feasibility.

Sample Time-Histories for a 300 m 2024 PDC25







Next Steps:

- Update the maneuver schedule for the 2024 YR4 case to match B-Plane knowledge.
- Conduct Monte Carlo studies to verify that the filter converges to the truth values implied by these covariance-focused studies.
- Study the mass measurement sensitivity to other measurement uncertainties and potential alternative payloads.

Acknowledgements:

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